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The National Atmospheric Release Advisory Center modelling and decision-support system for radiological and nuclear emergency preparedness and response

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Abstract: This paper describes the tools and services provided by a national centre for modelling the environmental and health impacts of airborne hazardous materials. This centre can provide emergency decision support information within minutes for a wide range of radiological, nuclear, chemical, and biological hazards from fires, industrial and transportation accidents, radiation dispersal device explosions, hazardous material spills, nuclear power plant accidents and nuclear detonations. Web- and internet-based software provides quick access to advanced modelling tools, as well as expert analyses from the centre. Model predictions include the 3D spatial and time-varying effects of weather, land use and terrain, on scales from the local to regional to global. Tools provide displays of plume predictions with affected population counts, detailed maps, and reports describing model assumptions, contamination and dose levels. On-scene information and measurements are used to refine model predictions.

Keywords: atmospheric dispersion modelling; decision-support system; measurement data assimilation.

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1 Introduction

The dispersion of radiological material in the atmosphere poses potential risks to human health. Releases may occur from accidents involving nuclear power plants, nuclear material processing and transportation of nuclear material. The post-cold-war proliferation of nuclear material has increased the potential for threats from radiological dispersal devices and nuclear weapons. In order to prepare for airborne releases and mitigate the resulting impacts, tools are needed that can accurately and quickly predict the environmental contamination and health effects.

A wide variety of tools are needed in order to characterise the airborne source, atmospheric transport and diffusion, surface deposition, resuspension and dose to humans from multiple pathways (air immersion, ground exposure, inhalation and ingestion). Equally important is to translate the assessment of dose into easily comprehensible guidance for critical decisions, such as evacuation, sheltering-in-place and relocation (NCRP, 2001) and to provide relevant decision-support information (such as affected population and other geographical data) needed by emergency responders and decision-makers. Finally, in order to facilitate timely decisions and protect lives, it is essential to quickly and simultaneously distribute common situational awareness products to decision-makers in multiple, collaborating agencies at different levels of government.

The National Atmospheric Release Advisory Center (NARAC) addresses these needs by providing tools and services that predict and map the probable spread of hazardous material accidentally or intentionally released into the atmosphere. Located at the University of California's Lawrence Livermore National Laboratory (LLNL), NARAC is a national support and resource centre for planning, real-time response, detailed studies and research into airborne hazards, involving nuclear, radiological, chemical, biological or natural emissions.

NARAC's origins date to the early 1970s, when the US Atomic Energy Commission (AEC) supported LLNL to develop an advanced modelling capability to assess impacts from airborne releases of radiological contamination. Sullivan et al. (1993) and Ellis et al. (1997) provide a description of NARAC's models, software systems, scientific validation and operations during its first two decades of existence. During this period, NARAC provided assessments of the consequences of the Three Mile Island and Chernobyl nuclear power plant accidents.

NARAC provides its operational tools and services to users under the sponsorship of several agencies. The primary sponsors of NARAC operation are the Office of Emergency Response in the US Department of Energy's (DOE) National Nuclear Security Administration (NNSA); the Interagency Modelling and Atmospheric Assessment Center (IMAAC) led by the US Department of Homeland Security (DHS) and the US Naval Reactor programme. NARAC is an integral part of the DOE's contribution to the Federal Radiological Monitoring and Assessment Center (FRMAC) (Wilber et al., 2006). NARAC provides support to over 40 individual DOE and US Department of Defense (DOD) facilities. NARAC also supports DOE's International Emergency Management and Cooperation (IEMC) programme to help strengthen worldwide emergency preparedness and to develop capabilities to respond to international nuclear events through collaborative projects with other governments and international organisations. The DHS science and technology directorate has supported the research and development of emergency response modelling systems, including atmospheric flow and dispersion modelling in urban areas. Under the auspices of the DOE, DHS and DOD, NARAC works with over 300 collaborating state and federal organisations involved in emergency preparedness activities.

According to the new US National Response Plan (DHS, 2004), the DHS-led IMAAC generates the single Federal prediction of atmospheric dispersions and their consequences utilising the best available resources from the Federal Government and 'provides a single point for the coordination and dissemination of Federal dispersion modelling and hazard prediction products that represent the Federal position during an incident requiring federal coordination'. Current collaborating agencies include the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), the Department of Defence (DOD), the DOE, the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA) and the Nuclear Regulatory Commission (NRC). The IMAAC was created under the auspices of the Homeland Security Council on 15 April 2004. NARAC is the designated primary initial provider of IMAAC capabilities.

This paper describes current capabilities, operational applications, recent advances and ongoing research within NARAC. Section 2 describes the meteorological, geographical, hazardous material property and other databases used by NARAC. An overview of the computer models used to simulate atmospheric flows, airborne dispersion and surface deposition is given in Section 3. Decision-support products, including dose to humans, protective action guides and geographical information displays, are covered in Section 4. The software systems used to collect data, automatically execute computer models and disseminate decision-support products in real-time are described in Section 5. The multidisciplinary staff, facilities and operations are summarised in Section 6. Testing, evaluation and applications of the NARAC models and other operational capabilities are reviewed in Section 7. The integration of measurement data with model predictions to produce refined and improved simulations is included in Section 8. Future research and development directions are described in Section 9.

2 Supporting databases

The NARAC mission – to provide near-real-time predictions of atmospheric dispersion anywhere in the world – requires access to large volumes of current and forecast weather data, and to extensive databases of population density, hazardous material source characteristics, radiological, chemical, and biological material properties, dose factors, dose limits and protective action guides.

NARAC continuously receives up-to-date surface and upper-air meteorological observations from the worldwide meteorological network via redundant communication links to the US Air Force Weather Agency (AFWA) and the US National Weather Service (NWS). Additional meteorological observations are supplied by NARAC-supported sites and several regional mesoscale networks (mesonets) in, and near the USA (including the western US MESOWEST network and NOAA Wind Profiler networks). Global and regional Numerical Weather Prediction (NWP) forecasts from the US Navy Fleet Numerical Oceanographic and Meteorological Center (FNMOC) and the NWS are obtained several times daily. NARAC also utilises an in-house version of the US Navy's COAMPS mesoscale NWP model.

NARAC maintains extensive geographical databases of terrain elevation and land-use classifications to specify the lower boundary conditions for its Three-Dimensional (3D) atmospheric flow and dispersion models. Global-coverage terrain elevation is provided by databases with 10 km horizontal resolution obtained from NOAA's National Geophysical Data Centre (NGDC), the US Geological Survey (USGS) data with 1 km resolution and the National Geospatial-Intelligence Agency's (NGA) Digital Terrain

Elevation Data (DTED) with 1 km, 100 m and 30 m resolution and approximately 60% coverage of the world. US terrain elevation is provided by the USGS Digital Elevation Model (DEM) database with 30 m resolution. Urban building elevation and morphology data, needed for specialised building-scale flow and dispersion model simulations, are obtained from a variety of sources.

Urban and rural land-use characteristic data are provided by the Global Land Cover Characteristics (GLCC) and Oak Ridge National Laboratory's (ORNL) LandScan database (1 km horizontal resolution, 24 land-use categories). US coverage is provided by the USGS Land Use Land Cover (LULC) 200-m resolution database and the USGS National Land Cover Database (NLCD) with 21 categories, 30 m resolution and 48 US state coverage.

NARAC uses population density data to estimate the number of people potentially affected by a particular contamination or dose level. Global population coverage is provided by ORNL LandScan data (30 min, or approximately 1 km, resolution, day–night average). US coverage for residential populations is provided by US Census Bureau data. A database from Los Alamos National Laboratory (McPherson and Brown, 2003) uses US Census Bureau residential data and augments it with business population (from the State Business Directory) and estimates of day–night worker migration, providing a population density database that accounts for time-of-day population variation for the entire USA on a 250-m resolution grid. For special events, NARAC's population databases can be manually adjusted to account for the additional people present (e.g. at a stadium or a convention for a special event).

NGA VMAP and ADRG databases provide global base maps for displays of geographical data. US maps and aerial imagery are provided by Geographic Data Technology, Inc., Census Bureau TIGER, USGS DRG, USGS DOQ and GlobeXplorer.

A specialised residential building leakiness database (for calculating the infiltration of exterior air into residential buildings) has been developed in collaboration with Lawrence Berkeley National Laboratory (Chan et al., 2004b). This database is derived from US Census data and studies of US building leakiness. A commercial building air infiltration modelling capability is currently in development.

3 Models

NARAC utilises a range of numerical modelling capabilities to support different types of release events, distance scales (local, regional, continental and global) and response times. Simpler, fast-running deployable models are used to perform screening calculations and fast initial response and can be used in the field when connections to the NARAC facility are not available. More detailed 3D dispersion models, coupled to real-time observational data and NWP model output, are used by scientific specialists for both near-real-time response and detailed assessments. Urban canopy parameterisations, the empirical Urban Dispersion Model (UDM) and building infiltration models provide enhanced understanding of urban effects. Computational Fluid Dynamics (CFD) models that explicitly resolve urban structures are used for high-fidelity applications including vulnerability analyses and planning studies.

3.1 Grids

NARAC's central system models (ADAPT and LODI) use the same type of grid system to store terrain elevations, land characteristics, meteorological fields, airborne hazardous material concentrations and surface deposition data. The grid system uses a continuous representation of the ground surface based on a piece-wise bilinear interpolation of grid-point terrain elevation data. The system supports run-time selection of both the number of grid points and grid resolution and can include variable resolution in both the vertical and horizontal coordinates. Variable vertical resolution provides appropriate representation of the meteorological fields, including higher resolution in the critical near-surface region. Variable horizontal resolution is used when warranted by topographical variation, meteorological data (metdata) density, plume dimensions or source location/geometry. Nested grids also can be used for modelling problems involving several spatial scales. NARAC software supports a variety of map projections required for a range of spatial scales from local to global.

3.2 Meteorological models

NARAC uses both diagnostic and prognostic (forecast) meteorological models. Forecast or NWP models predict the time evolution of the atmospheric flow field by solving the conservation equations for mass, momentum and thermodynamic energy. The models incorporate relevant physical processes for moisture, cumulus convection and radiation, as well as parameterisations of subgrid-scale turbulent mixing.

The primary internal NARAC source of prognostic mesoscale model data is an in-house version of the Naval Research Laboratory's Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS) model (Hodur, 1997), which can be relocated to produce forecasts for any location in the world. NARAC has developed an urban canopy parameterisation for COAMPS, which has been shown to improve the representation of urban flow fields (Chin et al., 2005).

Forecast metdata are continuously obtained from outside agencies. Specifically, NARAC regularly receives data from:

1 the NWS GFS model (1.0° horizontal resolution, 3-hourly data out to 180 hr from model initialisations at 0000, 0600, 1200 and 1800 UTC and also 0.5° horizontal resolution, 3-hourly data out to 84 hr from model initialisations at 0000, 0600, 1200 and 1800 UTC)

2 the US Navy NOGAPS model (1.0° horizontal resolution, 3-hourly data out to 72 hr from 0000 and 1200 UTC initialisations)

3 the NWS ETA model (40 and 12 km horizontal resolution, 3-hourly data out to 84 hrs for initialisations at 0000, 0600, 1200 and 1800 UTC) and

4 the NWS RUC model (20 km horizontal resolution, 1–3 hourly data from hourly initialisations, continuing with 3-hourly data from 4 to 12 hr for initialisations at 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC).

For special applications, data can be obtained from regional simulations made by the FNMOC using the NRL COAMPS mesoscale model, or by the US AFWA using the MM5 model.

The ADAPT model (Sugiyama and Chan, 1998) assimilates data from observations (e.g. from surface stations, rawinsondes and profilers) and/or weather forecast models, as well as land-surface data, for use in the NARAC dispersion model, LODI. ADAPT constructs meteorological fields (mean winds, pressure, precipitation, temperature, turbulence quantities, etc.) based on a variety of interpolation methods and atmospheric parameterisations (Chan and Sugiyama, 1997; Sugiyama and Chan, 1998). ADAPT produces non-divergent wind fields using an adjustment procedure based on the variational principle and a finite-element discretisation. A finite-element representation is used for spatial discretisation because of its effectiveness in treating complex terrain and its flexibility in dealing with variable resolution grids. The solution is obtained via a choice of conjugate gradient solvers, using a stabilisation matrix to improve computational efficiency.

In emergency response mode, ADAPT is typically run by ingesting real-time observational data. Terrain and atmospheric stability effects are introduced through the variational mass-conservation adjustment process. Land-surface characteristics and surface heat and momentum fluxes can be used to diagnose horizontally averaged properties of the mean wind and turbulence, using similarity theory relationships. ADAPT diagnostic simulations typically require under a minute to execute.

ADAPT can estimate turbulence quantities required by the dispersion model, LODI, using similarity theory scaling relationships. The methods summarised by van Ulden and Holtslag (1985) are used to estimate surface heat and momentum fluxes and turbulence scaling parameters (e.g. friction velocity, u_*; Obukhov length, L; convective velocity scale, w_* and boundary layer depth, h) from near-surface meteorological observations and land-use data. The turbulent diffusivities, K_x, K_y and K_z, are calculated as a function of height and horizontal location using these scaling parameters and similarity theory relationships described by Nasstrom et al. (2000).

3.3 Source characteristics

Atmospheric dispersion models require a source term that describes characteristics such as the mass or activity released to the atmosphere, the emission rate, height, spatial distribution and particle size distribution. For nuclear power plant accidents, NARAC relies on the NRC's RASCAL model (Sjoreen et al., 2001) for source term estimates based on plant conditions. In collaboration with the NRC, NARAC has developed an interface to quickly import nuclear power plant accident source terms from RASCAL into the NARAC dispersion model. For radiological dispersal devices (such as explosives and sprayers), NARAC uses source characteristics from Sandia National Laboratories (Harper et al., 2006). The gross activity, spatial distribution and particle size distribution of the stabilised nuclear debris cloud for nuclear detonation sources are derived from an approach used by Harvey and Serduke (1979). Buoyancy- and/or momentum-driven plume rise from continuous sources such as fires or stack emissions is computed inside the NARAC dispersion model, LODI, as described below. The CAMEO/ALOHA software and associated databases (EPA, 1999a,b) are used for chemical material properties and toxic industrial chemical releases mechanisms (such as leaking tanks).

3.4 Gaussian plume and puff models

Fast-running Gaussian plume and puff dispersion models are valuable tools for local-scale predictions, rapid initial response to an incident and quick screening calculations to assess the magnitude of a hazard. Gaussian plume models are attractive for their relative simplicity of mathematical formulation (analytic expressions), limited input parameter requirements and computational speed. Gaussian plume models typically use only a single constant wind velocity and general categories of turbulent mixing (using a stability class) to parameterise turbulence diffusion (derived semi-empirically from experiments using near-surface releases). These models are therefore valid only for near-surface dispersion over short distance and time scales for which these assumptions are valid. However, they can be reasonably reliable in situations involving simple flows, such as unidirectional steady-state flow over relatively flat terrain.

NARAC software tools incorporate and/or interface with several Gaussian plume and puff models. NARAC software allows users to run the Hotspot Gaussian plume model (Homann, 1994), which provides emergency response personnel and emergency planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. Hotspot predicts dispersion and deposition using the Gaussian plume equation and provides a fast and usually conservative means for estimating the radiation effects associated with the short-term (less than 24 hr) atmospheric release of radioactive materials. It includes options for dispersion of continuous plumes, explosions, fires and ground resuspension (area contamination). Interfaces to share chemical information between NARAC software tools and the NOAA/EPA CAMEO/ALOHA (EPA, 1999b) toxic industrial chemical database and Gaussian plume modelling system have been developed.

Gaussian puff models can incorporate temporal, horizontal and vertical variations in meteorological conditions. Such models can therefore be used over a large range of distances and scales. We are developing the ability to run the urban-scale UDM Gaussian puff model (Griffiths et al., 2002) within the NARAC software system. The UDM is an empirical urban model, which includes the time- and space-averaged effects of buildings and building complexes on transport and diffusion.

3.5 Explosive prompt effects models

Conventional or nuclear explosions produce potentially harmful, prompt effects from blast overpressure, thermal radiation or ionising radiation. NARAC software predicts conventional high explosive blast overpressure effects using the Sandia National Laboratories BLAST model, which utilises overpressure relationships published by Caltagirone (1986). Prompt effects from nuclear detonation associated with direct blast injury, tumbling/impact, thermal injury and prompt radiation are predicted using the Sandia NUKE model, which utilises relationships published by Glasstone and Dolan (1977). A Nuclear Explosion programme in Hotspot software provides a simple, PC-based deployable tool for predicting the effects of a surface-burst nuclear weapon, including prompt effects (from neutron and gamma radiation, blast and thermal radiation) and fallout information (Homann, 1994).

3.6 Lagrangian Monte Carlo dispersion and deposition modelling

For regional to global scale atmospheric dispersion, NARAC uses a 3D Lagrangian stochastic, Monte Carlo atmospheric dispersion model that is coupled to the meteorological models, described above. Numerical methods based on the Lagrangian approach have several advantages because they are meshless. The accuracy of an individual particle trajectory calculation using a Lagrangian stochastic method is not dependent on grid resolution or the number of trajectories computed. Lagrangian methods can resolve point sources without additional computational cost or an approximate subgrid parameterisation, unlike Eulerian methods or hybrid Eulerian-Lagrangian, particle-in-cell methods.

The NARAC 3D dispersion model, the Lagrangian Operational Dispersion Integrator (LODI), simulates the processes of mean wind advection, turbulent diffusion, radioactive decay, first-order chemical reactions, wet deposition, gravitational settling, dry deposition and buoyant/momentum plume rise. This model solves the 3D advection–diffusion equation:

$$\begin{aligned}\frac{\partial C}{\partial t} = &-\overline{u}\frac{\partial C}{\partial x} - \overline{v}\frac{\partial C}{\partial y} - \overline{w}\frac{\partial C}{\partial z} + \frac{\partial}{\partial x}\left(K_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial C}{\partial y}\right) \\ &+ \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + w_s \frac{\partial C}{\partial z} - \Lambda C - \lambda C + Q\end{aligned} \tag{1}$$

where C is the mean air concentration of a species; $\overline{u}, \overline{v}$ and $\overline{w}$ are the mean wind components in the x-, y- and z-directions, respectively; t is time; K_X, K_Y and K_Z are the eddy diffusivities for the three coordinate directions; w_s is the absolute value of the gravitational settling velocity; Λ is the precipitation scavenging coefficient; λ is the decay constant for radioactive decay (or the rate constant for first-order chemical reaction) and Q is the source term. Additional terms (not shown) are used to calculate the production of radionuclides due to the decay of other radionuclides in a decay chain.

Equation (1) is solved using the Lagrangian stochastic, Monte Carlo method, in which deterministic particle displacements due to the mean wind are calculated using the Runge-Kutta methods described by Leone et al. (1997). The displacement of a particle due to turbulent diffusion is performed using the method developed by Ermak and Nasstrom (2000) based on a skewed, non-Gaussian particle position probability density function, necessary for the efficient simulation of diffusion in inhomogeneous turbulence (especially near the ground surface).

The source term, Q, in Equation (1) is specified using input parameters for the initial spatial distribution of source material (options are provided for point, line, 3D Gaussian, and uniform spherical distributions) and the total source mass (or activity) emission rate, q. Both the spatial distribution and emission rate may change in time, in order to simulate moving and time-varying sources. For an aerosol source, the mass (or activity) distribution (i.e. the mass of the species of interest as a function of particle size) can be specified via input parameters specifying a lognormal distribution or from tabular input.

The LODI dispersion model includes parameterisations for the vertical rise of bent-over plumes from continuous sources due to initial vertical momentum and/or buoyancy. Analytic expressions reviewed by Weil (1988) are used for the mean height and radius of the plume as a function of time. The final rise of a plume is limited by several factors, including the intensity of the ambient turbulence and the presence and strength of stable layers at or above the source. The model uses the minimum rise found from separate calculations of the rise due to each of these effects. During the initial plume rise phase of a particle trajectory, an additional mean vertical velocity due to plume rise is added to the mean vertical velocity of the particle due to other processes (mean wind, gravitational settling). Diffusion during the plume rise phase is calculated using an effective diffusivity, assuming that the standard deviation of the spatial distribution of material in the plume is proportional to the plume radius. In the absence of modelled or observed temperature data, the ambient potential temperature gradient is assumed to be zero in the neutral and unstable Atmospheric Boundary Layer (ABL) and a similarity theory temperature profile is used in the stable ABL. The standard atmosphere temperature gradient ($-0.0065°\ m^{-1}$) is used above the ABL.

The terminal settling velocity, w_s, for aerosol particles is calculated using the particle diameter, particle density, air density and air viscosity derived from methods described by Hinds (1982). Different methods are used based on the Reynolds number of the flow around the falling particle. For particle Reynolds number, Re < 1, Stokes' Law is valid and is used to calculate the terminal settling velocity. For Re > 1, Stokes' Law is not valid and we use the table-based method described by Hinds (1982).

Dry and wet deposition of contaminants are simulated by LODI. A deposition velocity, v_d, is used to parameterise the effects of all near-surface dry deposition processes below a reference height, including turbulent and molecular diffusion to the surface, inertial impaction on the surface, absorption by the surface as well as gravitational settling. The deposition velocity for gases ($w_s = 0$) is $v_d = 1/r_T$, where r_T is the total deposition resistance (e.g. Wesely and Hicks, 1977). For particulate matter ($w_s > 0$), the deposition velocity is calculated according to (Sehmel and Hodgson, 1978).

$$v_d = \frac{w_s}{1 - e^{-w_s/r_T}} \tag{2}$$

Dry deposition of material onto the surface is calculated by depleting the mass of computational particles near the surface, so that the flux of material to the surface is consistent with this deposition velocity (Leone et al., 2005). By depleting mass from all particles near the surface, instead of entirely removing a fraction of the particles, the statistical significance of both the deposition and air concentration calculations is greatly improved (by maintaining a larger computational particle count for both calculations). Precipitation scavenging and wet deposition is calculated using the size distributions of both the precipitation and the contaminant particles, and the fall velocities of both, as described by Loosmore and Cederwall (2004).

3.7 Building-scale CFD models

For detailed studies of flow and dispersion of airborne material around buildings and in the urban environment, NARAC uses a CFD model. While CFD models are computationally expensive compared to simpler modelling approaches, they are capable of simulating the dynamics of turbulent flows and can capture high-resolution features, such as flow jetting between obstacles, impingement and separation regions, wake vortices and recirculation zones caused by obstacles or terrain features. One of the important phenomena that CFD models capture is the lingering of contaminant material in recirculation zones behind buildings, after most of the material has transported downwind. CFD models using Large Eddy Simulation (LES) are able to capture turbulent fluctuations and peak concentrations.

The FEM3MP CFD model (Chan and Stevens, 2000) is based on solving the 3D, time-dependent incompressible Navier-Stokes equations on massively parallel computer platforms. The numerical algorithm uses a finite-element representation for accurate representation of complex building shapes and variable terrain, together with a semi-implicit projection method and modern iterative solvers for efficient time integration. Physical processes treated in FEM3MP include turbulence modelling via the Reynolds Averaged Navier-Stokes (RANS) and LES approaches, atmospheric stability, aerosols, UV radiation decay of biological agents, surface energy budget and vegetative canopies. A next-generation version of FEM3MP, the Adaptive Urban Dispersion Integration Model (AUDIM) is currently under development.

3.8 Parallelisation

Key numerical models are parallelised to take advantage of the shared and distributed memory run-time environments that are available in NARAC's computer systems. Parallelisation of the models improves computational performance and is particularly important for high-resolution simulations or complex source applications. NARAC models utilise a parallel implementation based on a combination of Message Passing Interface (MPI) and OpenMP, in order to support both multiprocessor and massively parallel computing platforms.

The LODI model has been parallelised by taking advantage of the inherently parallel nature of Lagrangian random-walk dispersion models (Larson and Nasstrom, 2002). A parallel version of the COAMPS model, based on horizontal domain decomposition, was developed in a joint LLNL and Naval Research Laboratory collaboration (Mirin et al., 2001). This version is being used operationally by the Navy and is being integrated into the NARAC system. FEM3MP and AUDIM are built on constructs, which allow optimal performance on high-performance computing platforms.

4 Dose, health effects and decision-support products

Atmospheric dispersion and deposition models predict quantities such as time-integrated or time-averaged air concentration, peak air concentration experienced at any interval during the total exposure time and accumulated surface deposition. These quantities are converted into products that are useful to a wide range of users, including emergency responders, support scientists, emergency managers and decision-makers.

NARAC products include maps showing areas in which dose limits are exceeded, areas in which protective action (sheltering, evacuation and relocation) limits are reached, estimated counts of the affected population and geographic reference data (e.g. roads, political boundaries, terrain, water bodies, aerial photography, critical facilities such as schools and hospitals). Other potentially valuable information included in NARAC products are map displays of meteorological observations and model wind fields.

Radioactive dose is calculated from model-computed air- and ground contamination values, using dose conversion factor databases provided by ORNL. For internal 50-year committed dose from inhalation, these factors were published by the EPA (1988) and are a function of radionuclide, chemical form and particle size. The factors are derived from the International Commission on Radiological Protections (ICRP) Publication 30 lung model and methodologies for internal dose. Optionally, inhalation dose conversion factors, based on the ICRP-66 lung model and ICRP 60/70 series methodologies (published by the EPA, 1999c), can be used. For external dose from both ground and air immersion exposure, dose conversion factors published by EPA (1993) are used. In addition, acute (24-hr) dose factors from Eckerman (2001) are used for estimating non-stochastic effects, from high acute radiation doses for applicable target organs (the lung, small intestine wall and red bone marrow).

Radiological dose limits from the US EPA (1992) for guiding protective actions (sheltering, evacuation and relocation) and for emergency workers engaged in property protection and life saving activities are automatically displayed as plume model contour areas on NARAC map products. Population data, dose-response models and risk factors are used to estimate the number of casualties from acute dose exposures and the number of latent cancer incidents from chronic doses using methodologies described by EPA (1992) and NCRP (1993).

For toxic chemical exposure, NARAC uses airborne exposure limits from the EPA's Acute Exposure Guideline Levels (AEGL), the American Industrial Hygiene Association's Emergency Response Planning Guides (EPRG) and the US DOE's Temporary Emergency Exposure Limits (TEEL). Up to three exposure levels are shown:

1 notable discomfort

2 serious/long-lasting effects and

3 life-threatening effects.

For chemical and biological warfare agents, lethal dosage levels are shown if those levels are attained.

NARAC report generator software developed in collaboration with Sandia National Laboratories is used to reliably and accurately assemble a detailed effects and consequences report, which combines effects contour maps, tables of plume centreline values, the assumptions, background and explanatory text relevant to the calculations.

5 Software systems

The current third-generation NARAC software system became operational in 2000. It is a fully automated client–server system with internet-oriented technologies and can handle multiple simultaneous users and events. The complete system allows automated 3D predictions of atmospheric plumes and their consequences to be delivered in less than 15 min. The software is deployed in a heterogeneous hardware environment that currently includes UNIX, Linux and Windows servers.

NARAC's software system utilises a multitiered distributed software architecture that provides real-time access to the global meteorological and geographical databases and atmospheric modelling tools. The software infrastructure is composed of two primary components:

1 the NARAC Central System (NCS) and

2 the NARAC Enterprise System (NES).

The Central System integrates a sophisticated modelling environment with data warehousing capabilities and contains tools to generate end-user products. In-house NARAC staff has direct access to the Central System. The NES provides user-friendly web and other internet-based tools that allow registered users to remotely access advanced NARAC services and to share products with other users. In addition, the NES has a stand-alone capability that allows remote users to run simple plume models when internet and other communication channels to the Central System are not available.

The NCS combines three major subsystems (the metdata, geospatial data and model execution subsystems) with an environment for advanced scientific analysis and visualisation. The metdata, subsystem manages the acquisition, archival and processing of meteorological observations from over 20,000 instrument sites. It also handles gridded forecast data from external sources (e.g. NWS, AFWA and FNMOC) and NARAC's in-house version of the COAMPS mesoscale model. The metdata subsystem allows temporally and geographically relevant data to be extracted for use in the model execution subsystem.

The geospatial or geodata subsystem manages the registration, archival and processing of multiple geographic data sets for use by the models, and in the analysis of model output and visualisation products. The geodata subsystem allows topically and geographically relevant data to be extracted for use in a specific region.

The model execution subsystem manages the lifecycle, parameters and supporting databases used by the suite of model input data preprocessing tools, atmospheric models and postprocessing utilities. The generation of products and the analysis of model results are also handled by the model execution subsystem.

The NCS utilises a distributed client–server framework employing the Common Object Request Broker Architecture (CORBA). CORBA is a vendor-independent open architecture used for application networking. The current Central System was designed and developed using an object-oriented approach. The core services are written in C++, while Java is used for user-interface clients and servers that support remote access. Key atmospheric models such as LODI and ADAPT are written in Fortran 90. An object-oriented database system is utilised for modest-sized data and metadata storage for very large data sets. Large data sets are stored in their native format or as NetCDF files.

The core Central System services run on Unix/Linux platforms, with the software and hardware architecture permitting multiple events to be run in parallel. Future advances of the NARAC system will include the integration of new models being developed via ongoing R&D efforts (e.g. CFD models and sensor-data-driven event reconstruction models). These models are computationally intensive and hence utilisation of high-performance computing resources will be necessary.

Development of the NES began in 2000. The NES allows remote users to 'reach back' to the NCS, share results and information with other users and operate in a stand-alone mode if reach-back connectivity is not available. The NES consists of three components: the Enterprise or Middle Tier, the NARAC web and the NARAC iClient. Information exchange between the Central System, Enterprise Tier and the iClient and NARAC web end-user tools is handled via Extensible Markup Language (XML) and Hyper Text Markup Language (HTML).

The Enterprise Tier handles all external user connections to NARAC, processes requests for calculations and forwards them to the Central System, stores and processes the results of calculation requests, delivers these results in the form of data files or web pages and handles user access and data security issues.

The NARAC web and iClient are end-user tools that allow remote access to the NCS via the Enterprise Tier. The NARAC web is a secure website that permits remote users to input simple release scenarios, automatically run NARAC models and view and manage the results of model runs. The iClient is a more sophisticated desktop application that provides NARAC reach-back capability and stand-alone operation using local models on a user's remote system. It was designed using Java and web-based technology to provide a platform independent tool for deployed emergency management analysts. The iClient is designed for subject matter experts, whereas the NARAC web is targeted at a wider audience. Currently, there are approximately 100 iClient and 1200 NARAC web external users.

6 Staff, facilities and operations

In 1996, the DOE funded the construction of a new emergency operations centre, computer centre and staff offices for NARAC at LLNL. NARAC's operations centre has uninterruptible power supplies, backup power generators and computer systems that support the models and software systems described above. The same building houses a modern training facility for hands-on classroom training of users and the offices of the multidisciplinary NARAC staff.

Locating the entire multidisciplinary NARAC team together in the same building provides a unique and ideal environment for developing and maintaining a state-of-the-science atmospheric dispersion prediction capability. The NARAC team, comprised of research, development and operational personnel, has substantial collective subject matter expertise in operational meteorology, atmospheric science, chemistry, numerical modelling, Geographical Information Systems (GIS), health physics, industrial hygiene, computer science, engineering and computer system administration.

In order to respond rapidly to emergency situations, NARAC maintains a 24-hr-per-day on-call staff. When an emergency occurs, NARAC operational staff members immediately begin providing technical and scientific support, including quality assurance of model input data and predictions. This support continues until all airborne releases are terminated, the hazardous areas are defined and mapped, the measurement data have been used to update model predictions and the long-term impacts are assessed. In addition to its regular services, the staff can also use NARAC's advanced modelling and visualisation tools to provide specialised products needed by users. The staff also provides support and training on NARAC tools and services.

NARAC's professional staff is primarily a centralised resource. A minimum team is comprised of an event operations manager, one or more operational support scientists and a customer support assistant. Depending on the event, the team also may include a health physicist, industrial hygienist, chemist, administrative assistant and computer technician. In-house software and model developers can support rapid customisation of tools to meet the needs of a particular incident response.

NARAC personnel are available for deployment to an incident location. The need for deployment is determined by the requirements for extensive NARAC support. Deploying a NARAC liaison at a FRMAC, has proven to be invaluable for facilitating information flow between on-scene emergency managers and NARAC and for fostering full utilisation of NARAC tools and services. The deployed team usually consists of one operational support scientist per shift.

7 Testing and applications

Emergency response modelling systems must be extensively validated in order to verify that they have been implemented properly, produce realistic predictions and are reliable in emergency conditions. NARAC models and software systems have been rigorously tested and evaluated in multiple ways. Before being used operationally, software quality is assured by testing in separate computer systems before moving to the operational system.

Evaluation of models includes the use of analytic solutions (known, exact mathematical solutions to the model equations) to verify that the numerical methods used are sufficiently accurate. Comparisons against tracer field experiment data are used to test and evaluate models for a range of real-world terrain and meteorological conditions. After-action reviews following actual atmospheric release events evaluate model usability, efficiency and reliability of models for real-world operations. Since the NARAC modelling system is designed to simulate cases involving both simple and complex terrain and multiple space and time scales (microscale, to mesoscale to continental scale), it must be tested under all these conditions. A few examples are presented in the rest of this section.

The metdata assimilation and interpolation algorithms in ADAPT have been successfully tested by comparison to observational data (Sugiyama and Chan, 1998). The non-divergence adjustment algorithm is verified against potential flow solutions and wind tunnel data (Chan and Sugiyama, 1997).

A series of tests using analytic solutions have been performed to verify that the LODI dispersion model accurately solves the advection-diffusion equation. Results for solutions to the 1D diffusion equation for linear and quadratic $K_z(z)$ have been given previously by Ermak and Nasstrom (2000). Comparisons have been made against analytic solutions for the following cases:

1 3D advection and diffusion from an instantaneous Gaussian source with constant mean wind, constant diffusivities and an impermeable lower boundary

2 1D vertical diffusion of a well-mixed, uniform spatial distribution with similarity theory $K_z(z)$ and impermeable upper and lower boundaries

3 3D advection and diffusion from a continuous point source with linear $K_z(z)$, constant wind, no downwind diffusion, travel-time-dependent K_y and impermeable lower boundary

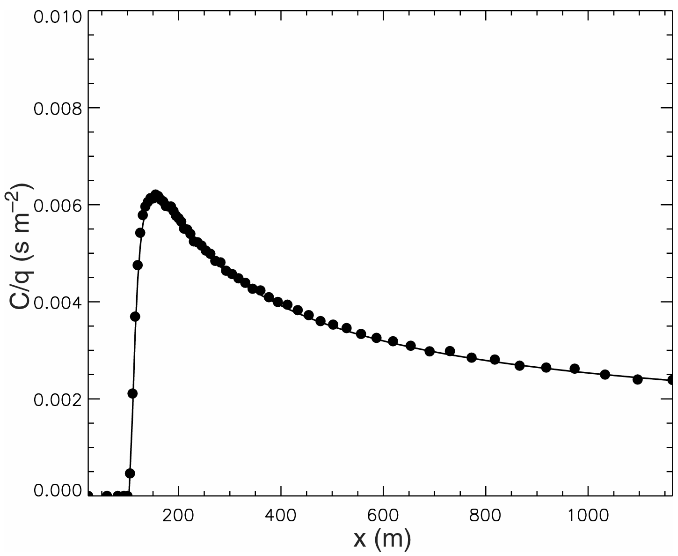
4 1D settling, surface deposition, radioactive decay and integrated ground exposure due to a uniform vertical concentration distribution of aerosol with zero wind and zero diffusivity and

5 2D advection and diffusion from a continuous point source with power law $\overline{u}(z)$, linear $K_z(z)$, zero downwind diffusion and an impermeable lower boundary.

These tests have been used to develop automatic time step restrictions (based on grid spacing, magnitude of the diffusivity and its gradient, magnitude of the wind speed components, boundary layer depth and decay time constant) that ensure accurate numerical solutions (less than 5% error in the computed quantities, air concentration and/or deposition, for each solution).

An example simulation result from the 2D (downwind distance, x, versus height, z) case of a continuous point source at z = 15 m, a power law $\overline{u}(z) = 5z^{0.2}$ m s^{-1} and a linear $K_z(z) = 0.1z$ m^2 s^{-1} (both typical of the neutral surface layer) is shown in Figure 1. In this simulation, a graded vertical wind grid was used with a minimum grid spacing of 0.25 m for the first three grid points near the surface and each succeeding vertical level having twice the spacing of the next lower level. A total of 10^5 particle trajectories were calculated. Concentrations were calculated by sampling particles on a grid with 3 m vertical resolution near the surface. Agreement between the numerical and analytic solutions for the mean air concentration is very good, verifying that the LODI model accurately simulates advection and diffusion in vertically inhomogeneous mean wind and turbulence.

Figure 1 Concentration (per unit source strength) versus downwind distance from analytic solution (curved line) and numerical model solution (circles) at 19.5 m above the surface for the 2D case of a power law wind speed and linear diffusivity.



Historically, NARAC has used a variety of tracer experiments for model testing and evaluation (Foster et al., 2000; Nasstrom and Pace, 1998; Sullivan et al., 1993). An example is the Project Prairie Grass experiment (Barad, 1958), which was used to test the ability of the ADAPT/LODI modelling system to simulate microscale dispersion. Continuous 10-min releases of SO_2 gas at a height of 0.46 m were conducted in an area of flat, arid grassland. Time-average concentrations were measured at $z = 1.5$ m on arcs 50, 100, 200, 400 and 800 m from the source and at heights of 0.5, 1.0, 1.5, 2.5, 4.5, 7.5, 10.5, 13.5 and 17.5 m on six towers located on the 100-m arc. The 20-min average wind and temperature were measured at a multilevel tower instrumented at 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0 m. A rawinsonde provided upper level wind and temperature data.

These observations were used by ADAPT to generate a wind field on a grid with 26 vertical levels which resolve the tower observation levels (grid levels at $z = 0, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, \ldots$, m). A zero-slip speed was imposed at the surface. The 10-min average crosswind velocity variance from a 2-m tower observation nearest the source location and closest to the gas release time was used to scale the horizontal velocity variance parameterisation. For the LODI dispersion simulation, 10^5 particle trajectories were computed and concentrations were calculated by sampling particles in a graded vertical grid with a 0.25 m vertical spacing at the surface and succeeding higher grid volumes spaced so that they were centred at the heights of the vertical tower concentration observations.

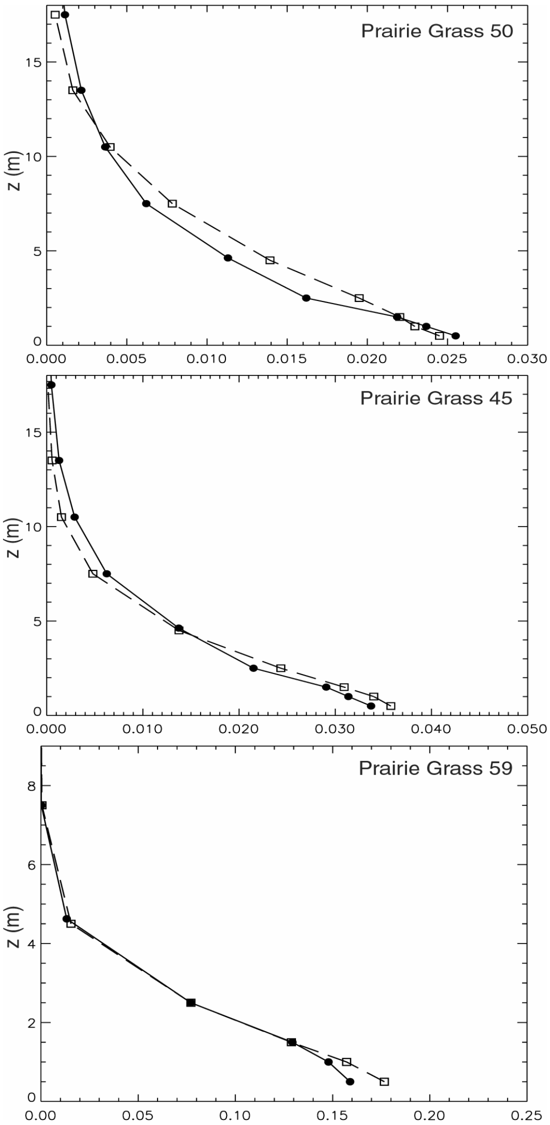
2D (downwind distance versus height) simulations were made to compare model results to the crosswind-integrated 100-m arc-observed concentrations computed by Wilson et al. (1981). We used values of L and u_* calculated by Wilson et al. from observed wind and temperature profiles assuming a surface roughness height of 0.005 m. Deposition velocity values were calculated using the method of Wesely and Hicks (1977) for estimating the total SO_2 deposition resistance. For the SO_2 canopy resistance, we also used their value for vegetation subject to water stress, 200 s m^{-1}. For stable conditions, values of h were set to the height of the nocturnal surface-based inversion, determined from the rawinsonde temperature soundings. For unstable conditions, h was set to the height of base of the elevated inversion layer in the observed temperature sounding.

Figure 2 shows comparisons of predicted and observed crosswind-integrated concentration profiles for the Prairie Grass experiments with a range of atmospheric stability: #50 (unstable), #45 (near neutral) and #59 (stable). These model results show good agreement with the observations for all three stability conditions and demonstrate the ability of the models to simulate dispersion in the vertically inhomogeneous mean wind and turbulence conditions found closer to the ground.

Figure 3 shows a comparison of air concentrations predicted using the ADAPT/LODI models compared to measurements from the Diablo Canyon tracer experiment (DOPPTEX) conducted along the central coast of California (Thuillier, 1988). This simulation is for SF_6 gas released at the site of the Diablo Canyon nuclear power plant. Figure 3 shows shaded contours of the simulated 1-hr averaged surface concentration from 1900 to 2000 UTC, overlaid on terrain contours and coastline. Also plotted are representative observed values of SF_6 air concentration (numerical values next to '+' symbols, which indicated sampler locations). The simulated plume concentrations match the complex pattern of the measured values well, with a few minor outliers.

Predictions from FEM3MP are verified and validated against data from wind tunnel (Chan and Stevens, 2000) and field experiments (Chan et al., 2004a,b). An example described by Chan (2004) using data from an URBAN 2000 field experiment (Allwine et al., 2002) is shown in Figure 4. The simulated dispersion experiment, Release 1 of Intensive Observation Period 7 (IOP7), was conducted under very light wind and highly variable wind direction. The source location is indicated by the horizontal line with approximate coordinates (500, −625). The small colour-coded squares plot the corresponding field measurement data (colours are chosen consistent with the contour level colours). Excellent agreement is obtained between the predicted concentration patterns and the observed data.

Figure 2 Vertical profiles of predicted (circles) and observed (squares) crosswind-integrated 100-m arc air concentration (per unit source strength) for Prairie Grass experiment #50 ($L = -26$ m, top figure); #45 ($L = -110$ m, middle) and #59 ($L = 7.3$ m, bottom)



Crosswind-integrated air concentration − C/q (s m^{-2}).

Figure 3 Air concentration (in ng m^{-3}) predicted using the ADAPT/LODI models (shaded contours) compared to measured 1-hr averaged air concentrations (numerical values next to '+' symbols, which indicated sampler locations from 1900 to 2000 UTC on August 31, 1986 from the Diablo Canyon tracer experiment. Contour lines represent terrain elevation in intervals of 100 m

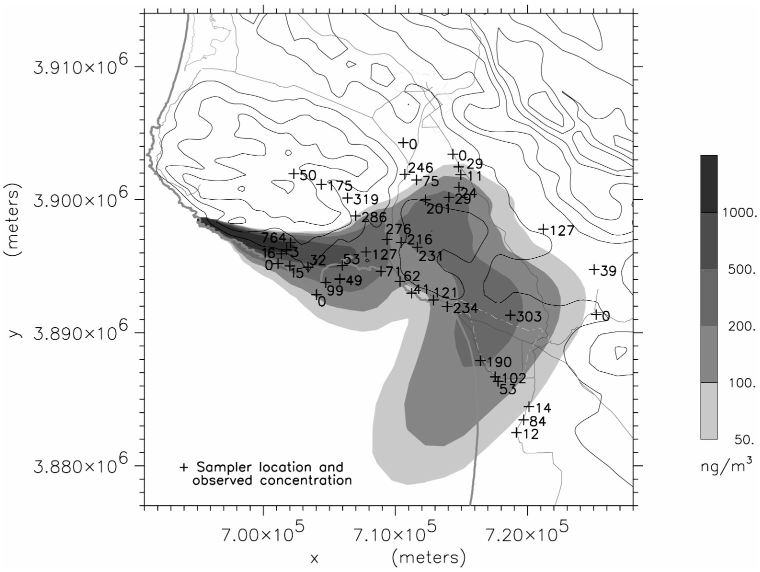
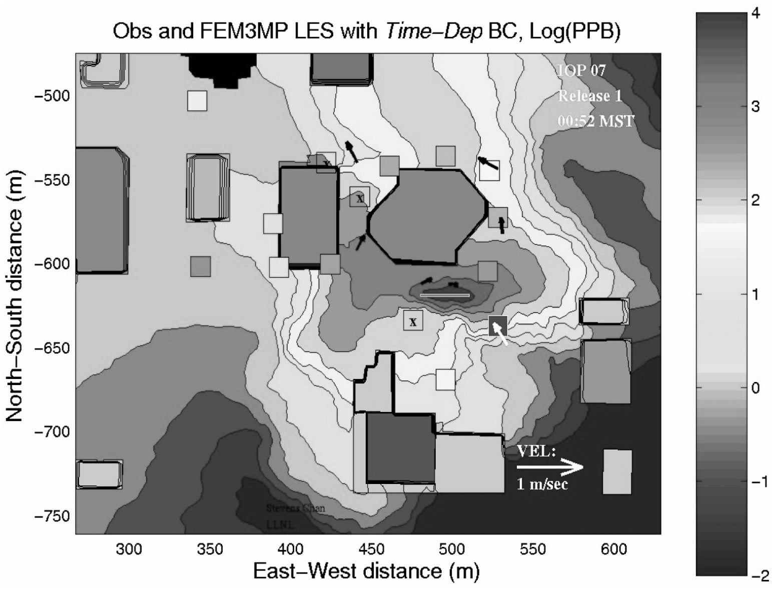


Figure 4 FEM3MP predicted time-averaged (for t = 50–55 min) concentration patterns on z = 1 m plane from a LES using time-dependent boundary conditions constructed from 1-sec sonic anemometer data collected on the rooftop of City Centre building. The gas sampler concentration observations are superimposed as small squares with the same colour scheme as the model concentration contours



Source: Chan (2004).

8 Integration of measurement data with model predictions

Because of limitations and uncertainties in input data (e.g. source term estimates) and other modelling assumptions, it is important to incorporate field measurements into predictions and assessments of dose as soon as possible during an incident or accident. For terrorist scenarios (e.g. an RDD) little may be known about the characteristics of the dispersed and airborne material. In this case, an idealised gas or aerosol source with a unit amount of material can be used to initially predict the downwind area in which to focus air- or ground monitoring activities. For nuclear power plant accidents, estimates of the source term may be available from plant conditions or data from a monitored stack. However, refinement of these estimates requires additional data.

Integration of measurements of radioactive contamination, airborne or on the ground, is especially valuable in the early and intermediate phases of an event. Even if only sparse measurement data are available, they can be used to calibrate initial model predictions to more accurately predict areas potentially needing protective actions (such as sheltering, evacuation or relocation). NARAC predictions, in turn, can help guide field teams to potentially contaminated areas that need monitoring. Models can then be used to interpolate between measurements and extrapolate beyond areas that have been monitored by measurement teams. By using this approach to the problem, low levels of contamination that are difficult to measure can be simulated more accurately. This methodology also can aid in helping to guide crop and food field sampling teams to areas in which contamination might result in an ingestion-pathway dose that exceeds regulatory limits.

Since its inception, NARAC has included the use of measurement data to update model predictions. Today, NARAC routinely participates in emergency response drills with organisations that collect air concentration, ground deposition and radiation exposure measurements. NARAC provides modelling support and works closely with regional and national measurement and dose assessment teams, including those at supported DOE and DOD sites and the DOE National Nuclear Security Administration (NNSA) Office of Emergency Operations' regional Radiological Assessment Program (RAP), Accident Response Group (ARG), Aerial Measurement System (AMS) as well as the Federal Radiological Monitoring and Assessment Centre (FRMAC).

NARAC works as part of the FRMAC to utilise measurement data for updating model predictions. Data are collected, assessed and stored in FRMAC databases and then electronically transmitted to NARAC. An XML file is being developed in a collaboration with the Remote Sensing Laboratory and Sandia National Laboratories to electronically transfer measurement data from FRMAC databases to the NARAC modelling system. XML has proven to be a simple, flexible, self-describing text format for this use. Data are stored with necessary metadata, such as units of measure, time of measurement, type of instrument, type of radiation or isotope.

NARAC scientists visually and statistically compare measured and computed values for each monitoring location point. A useful statistic is the average ratio of measured and computed values. These ratios provide good statistical measures for values that can vary over many orders of magnitude and can be used to scale the airborne source amount assumed in the model. A range of values for uncertain model input data (in particular wind data from several possible sources, particle size distributions and release heights for buoyant releases) are analysed to determine the input data that result in the best-fit model predictions, as measured by the measured-computed ratios.

Examples of NARAC's use of field measurements to update model predictions and estimate source terms include the Uranium Criticality accident at Tokaimura, Japan, in 1999 and the accidental melting of a Cesium source at a steel-processing facility in Algeciras, Spain in 1998 (Vogt et al., 1999).

9 Future research and development

In order to meet the challenges of future threats, an expanded set of capabilities may be required. An improved understanding of the ABL flows for stable, nocturnal, transitional, urban and coastal conditions is needed. Significant improvements in fidelity will result from a deeper understanding and new models of key physical processes, such as precipitation scavenging, resuspension, multiphase chemical kinetics, explosive releases and fires. For example, advanced approaches to simulating the time-dependent resuspension flux of deposited contamination (Loosmore, 2002) show promise for more realistic simulation of material resuspended after deposition onto ground surfaces.

The accuracy of predictions of the consequences of airborne hazardous material release events can be significantly improved by incorporating higher resolution, more representative metdata from local observational networks (mesonets), radar-derived precipitation and satellite analyses of winds, temperatures and clouds. Remote sensing data from lidars, wind profilers, radar and/or sodar systems can provide more realistic detailed metdata field for important quantities such as 3D-wind field, turbulence and mixing layer depth. NWP models can make use of additional meteorological observations to improve forecasts using data assimilation algorithms.

An emerging aspect of emergency response is the importance of methods for incorporating measurement data into predictions and analyses. Sensor data networks and real-time data feeds are needed to supply new meteorological and contaminant concentration measurement and new simulation tools are needed to interpret and assimilate this data.

Automated techniques for optimising model simulations using air and ground contamination measurements hold promise for faster refinement of uncertain model input variables, such as the source term. The development and operational use of event reconstruction tools is now becoming feasible due to the convergence of numerical modelling approaches, remote and deployable sensor technologies, high-performance computing and operational deployments of detector networks. These technologies are at the forefront of a revolutionary new paradigm for treating dynamic complex problems, which involve mutual optimisation of sensor data and models (the use of data to steer models and of models to guide data collection). A variety of approaches are being pursued, including heuristic methods (backward trajectories and ensemble simulations), Bayesian-inference stochastic sampling algorithms and non-linear optimisation. A LLNL approach couples data and predictive models with Bayesian inference and stochastic sampling to provide backward analyses to determine unknown source characteristics, optimal forward predictions for consequence assessment and dynamic reduction in uncertainty as additional data become available (Kosovic et al., 2005). These techniques can greatly aid an effective response to an unexpected radiological event that requires rapid quantitative estimation of the source term(s) based upon the available data, in order to provide the best possible predictions of transport and the resulting health risks to the exposed population and emergency responders. For practical application in real-time, sensor-driven modelling techniques must be integrated into information systems to combine automated data acquisition, analysis, display and distribution of predictions and decision-support products.

Uncertainty estimation is urgently needed for proper interpretation of simulation results. Ensemble weather forecasts can provide estimates of natural variability and forecast errors. A full uncertainty analysis of a release event would take into account the uncertainties in all input parameters (e.g. the meteorological fields and source attributes), incorporate the sensitivity of the model outcomes to those parameters, and produce quantitative uncertainty ranges for output results of interest. Monte Carlo analysis builds a probability distribution for predictions from a suite of model runs, generated from a randomly sampled set of input variables. Response Surface Methodology (RSM) is an alternate approach, which constructs uncertainties from a suite of runs, but utilises classical experimental design theory to generate the inputs for the event simulations. Sensitivity analysis decouples input uncertainty from model processes algorithms to provide an understanding of the sensitivities of model outcomes to the input parameters. Computed sensitivities then can be recoupled with input uncertainties to quantify prediction uncertainty. Methods must also be developed for interpreting and presenting uncertainty estimate and guidance to users and responders.

In order to more accurately characterise dispersion, deposition and dose, source properties – such as particle size distribution, isotope inventories and buoyant rise – for gas and aerosol released from nuclear and conventional explosions need to be better characterised, and need to account for different types of source material and different urban and rural land characteristics. Continued advances in the prediction of gas and aerosol infiltration into buildings and the coupling of indoor and outdoor transport models, is needed in order to better predict dose and effects for indoor population.

10 Summary

This paper has described the current capabilities of the NARAC for hazardous airborne material dispersion predictions. In order to accomplish NARAC's mission of providing real-time atmospheric hazard predictions and detailed assessment, a wide range of supporting databases, computer models, software systems and services have been integrated together. These include the following:

- methods of calculating source term data for nuclear weapons, nuclear power plant accidents, explosive sources and non-explosive sources (e.g. liquid dispersion and fires)
- automated, real-time, global meteorological observation acquisition (including global observation network, regional networks and local networks)
- automated collection and storage of continental- and global-scale gridded meteorological analyses and forecasts from several US agencies
- global terrain and geographical information (including land use/cover and maps) databases
- meteorological models for 3D, regional-scale flows with terrain effects

- computation of prompt effects including conventional explosive blast effects and the prompt effects of nuclear detonation associated with direct blast injury, tumbling/impact, thermal injury and prompt radiation (effects are quantified in terms of injury and fatality counts)
- 3D dispersion models with time-varying source properties and meteorological conditions from local-, regional- and global-scale meteorological models, including spatially-varying, aerosol-size-dependent and rain-rate-dependent precipitation scavenging
- CFD models capable of simulating the details of building-scale flow and dispersion for detailed planning and consequence assessments
- continuous stack emission (momentum- and/or buoyancy-driven) and fire (buoyancy-driven) plume rise source models
- dispersion models that simulate the decay and in-growth of radionuclides in decay chains before release, during atmospheric transport, and after deposition
- dose factor databases for inhalation, ground exposure and air immersion exposure modes (function of radionuclide, chemical form and particle size)
- affected population estimates using time-dependent population density databases
- tool to reliably and accurately assemble final consequence reports that include contour maps, graphs, tables and assumptions and background material relevant to calculations
- software tools for remote access (via secure network, internet, wireless or dial-up) to NCS automated model predictions, with user interfaces for both specialists and non-specialists to control models and display geographical information
- fast-running steady-state, local-scale and Gaussian-plume dispersion modelling tools deployed for use
- website for distribution of model products, consequence reports and background information to multiple, authorised agencies and users over network, wireless or dial-up communications links
- semi-automated software tools for entering field measurement data, graphically and statistically comparing measurements and model predictions, and refining model predictions to fit measured data
- 24 × 7 on-duty or on-call technical and scientific support staff.

NARAC's numerical models and software systems are continuously tested to evaluate their performance, and assure they are ready to respond. Testing using analytic mathematical solutions, field experiments and actual accidents has shown that the NARAC modelling system can simulate airborne dispersion over scales ranging from local to regional to continental scales. Integration of measurement data to update and refine model predictions is a key aspect of NARAC's capabilities.

Real-world incidents have proven the value of NARAC tools and services over a 26-year history. This history has shown that success in meeting operational challenges depends on

1. a multidisciplinary staff to provide expertise in the broad range of disciplines needed for analysing the consequences of airborne hazards (from sources to effects)
2. maintaining a real-time computer system with a comprehensive set of modelling tools and supporting meteorological, geographical and hazardous material databases
3. continuous integration of the results of a research and development programme that is driven by operational needs
4. the integration of measurement data and model simulations and
5. rigorous testing and evaluation of both modelling system components and the operations as a whole.

Research and development is ongoing today and includes work on sensor data assimilation into model predictions, urban effects on flow and transport, deposition and resuspension, high-performance computing, model uncertainty estimation, source characteristics, indoor exposure prediction and GISs.

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